Remarks

The Office Action mailed March 17, 2003 has been received and reviewed. Claims 1, 13, 27, and 35 having been amended, the pending claims are claims 1-44. Reconsideration and withdrawal of the rejections are respectfully requested.

Claim Amendments

Claim 1 was amended to clarify the invention.

Claim 13 was amended to clarify the invention.

Claim 27 was amended to clarify the invention.

Claim 35 was amended to clarify the invention.

No new matter was added. These amendments do not have a limiting effect on the claims. The amendments clarify the invention by including terminology that relates to the present invention being in the field of ellipsometry. The present invention has consistently been limited to ellipsometry and the amendments provided herein are only to clarify this limitation. As the claims pending have not been substantively amended, only clarified (i.e., the field of the invention has always been ellipsometry), an Advisory Action indicating that the amendment will not be entered due to amendments requiring a new search would be inappropriate.

Applicants have amended certain claims to provide definition for certain terms therein. It is Applicants' position that such terms have always had the definition as presented in the now amended claims in view of the specification, and therefore, such amendments do not provide a narrowing effect thereon. In other words, the amendments only clarify the claims, however, the scope of the claims is intended to be the same after the amendment as it was before the amendment.

The 35 U.S.C. §102 Rejection

The Examiner rejected claims 1, 4, 9, 12-14, 22, 24, 27, and 35-37 under 35 U.S.C. §102(b) as being anticipated by Kino et al. (U.S. Patent No. 5,022,743). Applicants respectfully submit that the above rejection should read "as being anticipated by Barrett (U.S. Patent No.

5,602,643)" and Applicants made that assumption in forming a response. Applicants traverse this rejection.

However, to further move this case towards issuance, Applicants have amended claims 1, 13, 27, and 35 as described above.

Claims 1, 13, 27, and 35

In regards to independent claims 1, 13, 27, and 35, the Examiner alleges that "Barrett discloses a measuring device comprises an objective lens (18), an illumination source (12), a spatial filter (40) is positioned at a plane of an exit pupil of the objective lens, and an analyzer portion (16, 50, 24) operable to generate polarization information based on the reflected light." Applicants traverse this statement.

For a claim to be rejected under 35 U.S.C. § 102(b), each and every element of the claim must be found in a single prior art reference. See M.P.E.P. § 2131.

Applicants submit that independent claim 1 is not anticipated by Barrett for at least the following reasons. Applicants submit that Barrett does not describe: an illumination source providing incident linearly polarized light such as the linearly polarized light used in ellipsometry (e.g., light that includes p and s wave components); reflected light from the sample such as analyzed in ellipsometry (e.g., reflected light that includes p and s wave components); or an analyzer portion operable to generate polarization information based on the reflected light such as performed in ellipsometry (e.g., wherein the polarization information is a function of the p and s wave components of the incident light having different reflectivities from the sample).

Ellipsometry is based on the use and measurement of polarized light. The name ellipsometry is derived from the fact that measurement of elliptically polarized light is a basis of ellipsometry. Elliptically polarized light is formed due to the simultaneous existence of the p and s wave components and the differences in reflectivity for the p and s wave components from the sample. The p and s wave components interact to provide ellipsometric information about the sample. The ellipsometer measures the ellipsometric information of the reflected light. Thus, ellipsometry requires the use of light which includes both p and s wave components. The

general definition, terminology, and equations that define ellipsometry are known. See, for example, Tomkins, H. et al., Spectroscopic Ellipsometry and Reflectometry, 1999, pp. 14-21; Chapter 2 of which is attached hereto for convenience.

Fundamental quantities of ellipsometry include the Psi, Delta (Ψ, Δ) pair. Such quantities can be defined in terms of the reflectivities of the p wave and s wave components, as described in the background section of the present application. In the context of ellipsometry, a p wave refers to a component of light in which the electric field is parallel to the plane of incidence of the sample to be measured and an s wave refers to a component of light in which the electric field is perpendicular to the plane of incidence of the sample to be measured.

Fundamental to ellipsometry is the usage of incident light which includes both a p wave component and an s wave component, and reflected light which includes both a p wave component and s wave component. This can be shown by considering, for example, the definition of a fundamental quantity of ellipsometry, Δ. The value of Δ is defined as $\delta_1 - \delta_2$, where δ_1 is defined as the phase difference between the p wave and s wave before the reflection, and δ_2 is defined as the phase difference between the p wave and s wave after the reflection (Tomkins, H. et al., p. 20). As shown, the definition of a fundamental quantity of ellipsometry requires that both the incident light and the reflected light include both a p wave component and an s wave component at the same time. Since these calculations involve differences between the p and s wave components, Δ is only defined when both the p and s wave components are provided. In other words, in conventional ellipsometry, the incident light includes both a p wave component and an s wave component at the same time, and the reflected light includes both a p wave component and an s wave component at the same time.

The present invention provides: an illumination source providing incident linearly polarized light such that the linearly polarized light includes p and s wave components; reflected light from the sample such that the reflected light includes p and s wave components; and an analyzer portion operable to generate polarization information based on the reflected light, wherein the polarization information is a function of the p and s wave components of the incident light having different reflectivities from the sample, as described in claim 1.

In contrast to ellipsometry, the interferometer described in Barrett operates with light that contains only p waves or s waves. Barrett states: "The placement of the linear polarizer 50 in the path traveled by lightwave L, makes it possible to selectively choose a polarized incident beam with the axis of polarization parallel or perpendicular to the plane of incidence (normally referred to in the art as S or P states)" (col. 5 lines 29-34). In other words, Barrett describes an interferometer device in which the incident and reflected light contains either p waves or s waves, but does not contain both at the same time.

Therefore, because Barrett is an interferometer and not an ellipsometer as described in the parent application, Barrett does not describe: an illumination source providing incident linearly polarized light such that the linearly polarized light includes p and s wave components; reflected light from the sample such that the reflected light includes p and s wave components; or an analyzer portion operable to generate polarization information based on the reflected light, wherein the polarization information is a function of the p and s wave components of the incident light having different reflectivities from the sample, as described in claim 1. Barrett never provides both the p wave component and the s wave component at the same time in either the incident light or the reflected light. Thus, Barrett does not anticipate claim 1.

Applicants submit that independent claims 13, 27, and 35 are not anticipated by Barrett for at least the same reasons as given above with respect to claim 1.

Furthermore, in regards to claim 27, Applicants submit that Barrett does not describe a spatial filter, wherein the spatial filter is used to break the azimuth symmetry of the incident or reflected light. Barrett describes a pupil mask used in combination with polarizers to provide a predetermined incident angle and to align the polarization of the incident light to either a p-wave or an s-wave with respect to the system (col. 4, lines 28-36). In the present invention, the pupil filter is used to break the symmetry of the ellipsometric signal to extract information (page 13, lines 3-7). The ellipsometric signal comes from the interference between the p and s wave component. Thus, both the p and s wave components are necessary to provide an ellipsometric signal. Barrett does not provide an ellipsometric signal because Barrett never provides light which includes the p and s wave components at the same time. Thus, Barrett does not provide a

spatial filter used to break the symmetry of the ellipsometric signal because Barrett does not provide an ellipsometric signal.

Furthermore, with respect to claim 35, Applicants submit that Barrett does not describe a spatial filter wherein the spatial filter is used to break the azimuth symmetry of the incident or reflected light, for the same reasons as described above related to claim 27.

For at least the reasons given above, Barrett does not anticipate claims 1, 13, 27, and 35.

Claims 4, 9, 12, 14, 22, 24, 36 and 37

In regard to dependent claims 4, 9, 12, 14, 22, 24, 36 and 37 which depend directly or indirectly from independent claims 1, 13, 27, and 35, such claims are not anticipated by Barrett for the same reasons as stated above for claims 1, 13, 27, and 35, and by reason of their own limitations.

The 35 U.S.C. §103 Rejection

The Examiner rejected claims 2-3, 5-8, 10-11, 15-21, 23, 25-26, 28-34, and 38-44 under 35 U.S.C. §103(a) as being unpatentable over Barrett (U.S. Patent No. 5,602,643) in view of Ghislain et al. (U.S. Patent No. 5,939,709). Applicants traverse this rejection.

Claims 2-3, 5-8, 10-11, 15-21, 23, 25-26, 28-34, and 38-44

In regard to dependent claims 2-3, 5-8, 10-11, 15-21, 23, 25-26, 28-34, and 38-44 which depend directly or indirectly from independent claims 1, 13, 27, and 35, such claims are not obvious over Barrett in view of Ghislain et al. in that they depend from independent claims 1, 13, 27, and 35 which applicants submit are lacking elements that are not described, taught, or suggested by Barrett or Ghislain et al.

Summary

It is respectfully submitted that the pending claims 1-44 are in condition for allowance and notification to that effect is respectfully requested. The Examiner is invited to contact Applicants' Representatives, at the below-listed telephone number, if it is believed that prosecution of this application may be assisted thereby.

Respectfully submitted for
LEGER et al.

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By: Sue Dombroske
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CHAPTER 2

Fundamentals

We are often called upon to measure samples of materials which are so small that quantities such as thickness cannot be determined by simply looking at them with the human eye. In such cases, we traditionally use a probe of some kind (electrons, ions, photons, etc.) and look at how the material of interest alters the probe. For spectroscopic ellipsometry and reflectometry, the probe is a light beam or electromagnetic wave in the UV, visible, or IR region. Electromagnetic waves and polarized light are treated in textbooks[1–3] and reference books,[4–7] on optics. In this section, we review the basic features which apply to ellipsometry and reflectometry.

2.1 DESCRIPTION OF AN ELECTROMAGNETIC WAVE

Historically, there were two schools of thought about light. One group considered light to consist of a beam of particles, and the other group considered light to consist of a wave of some sort. Sir Isaac Newton was the last great champion of the particle theory (until Albert Einstein discovered the photoelectric effect). After Newton, most scientists considered light to be a wave, although it was not at all clear what was *waving*.

The description of light as an electromagnetic wave continued to be developed in a rather fragmentary way until James Clerk Maxwell (1831–1879) provided a unifying description in a paper presented before the Royal Society in 1864. In *A Dynamical Theory of the Electromagnetic Field*, Maxwell proposed a theory which required the vibrations to be strictly transverse (perpendicular to the direction of propagation) and provided a definite connection between light and electricity. The results of this theory were expressed as four equations which are known as Maxwell's equations.

Maxwell's equations and the resulting wave equation are analogous to a differential equation which describes the forces on a body and the resulting equation which describes the motion of the body as a function of time. Maxwell's equations and the derivation of the wave equation are presented

in several texts[3] and reference books.[4,5] In this introduction, we simply list the wave equation. This is treated in detail in Appendix B.

Briefly, an electromagnetic wave is a transverse wave consisting of an electric field vector and a magnetic field vector, both of whose magnitude is a function of position and time. The electric vector and the magnetic vector are mutually perpendicular and are both perpendicular to the direction of propagation. It is generally accepted that the human eye reacts to the electric vibration. The two are not independent, and specification of the electric field vector completely determines the magnetic field vector. For these reasons, and for simplicity in general, we consider only the electric field vibration.

Th equation for an electromagnetic plane wave can be expressed several ways. Its purpose is to describe the electric field as a function of position and as a function of time. If we consider motion in one dimension only, the solution to the wave equation can be expressed as

$$E(z, t) = E_0 \sin\left(-\frac{2\pi}{\lambda}(z - vt) + \xi\right) \tag{2.1}$$

where E is the electric field strength at any time or place, E_0 is the maximum field strength or *amplitude* of the wave, z is the distance along the direction of travel, t is the time, v is the velocity of the wave, λ is the wavelength, and ξ is an arbitrary phase angle (which will allow us to offset one wave from another when we begin combining waves).

Figure 2.1 shows a pictorial illustration of such a wave with the electric field waving in the vertical direction. In this instance, we show the electric field as a function of position, with a constant time. For comparisons later when we discuss polarized light, we identify the places where the electric field is maximum, minimum, and zero.

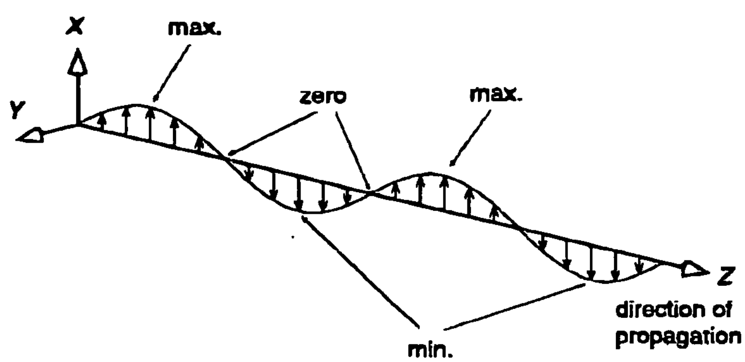

Figure 2.1 The electric field is shown schematically as a function of position, at a fixed time.

If we consider three dimensions (vector notation) and a circular function which is a bit more general than the sine function, a solution to the wave equation which comes from Maxwell's equations is

$$\bar{E}(\bar{r}, t) = \hat{E}_0 \exp\left(\frac{-j2\pi\tilde{N}}{\lambda}\bar{q}\cdot\bar{r}\right)\exp(-j\omega t) \tag{2.2}$$

where $\bar{r}$ is the position vector, $\bar{q}$ is the unit vector in the direction of wave propagation, $\tilde{N}$ is the complex index of refraction (to be introduced later), ω is the angular frequency, and j is the imaginary number ($\sqrt{-1}$).

We cannot measure the electric field amplitude of the electric field directly because of the high angular frequency. Instead, we measure the flux of energy of the radiation. The quantity of energy being transferred across a unit area which is perpendicular to the direction of propagation is called the *intensity* of the wave (here denoted as I). The intensity I is proportional to the square of the amplitude of the wave, that is,

$$I \propto E_0^2 \tag{2.3}$$

We note in passing that the quantity which is utilized in reflectometry is the intensity of the wave, whereas the quantity which is utilized in ellipsometry is the amplitude of the wave. Although light waves can occur in several different forms (i.e., spherical, plane, etc.), we shall deal exclusively with plane waves.

2.2 THE EFFECT OF MATTER ON ELECTROMAGNETIC WAVES

2.2.1 The Complex Index of Refraction

When a light beam (plane wave) arrives at an interface between air and another material, as depicted in Figure 2.2, several phenomena can occur. The wave generally slows down, changes direction, and in some instances begins to be absorbed. Some of the light is reflected back into the first medium (air) and does not enter the second medium. From an optics point of view, the second material is characterized by its complex index of refraction, $\tilde{N}_2$, and its thickness (in this case, taken to be infinite). In general, the complex index of refraction $\tilde{N}$ is a combination of a real number and an imaginary number and is designated as

$$\tilde{N} = n - jk \tag{2.4}$$

where n is called the *index of refraction* (sometimes leading to confusion), k is called the *extinction coefficient*, and j is the imaginary number.

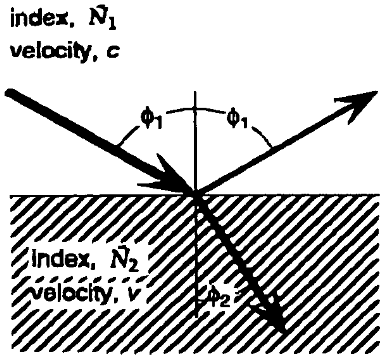

Figure 2.2 Light interacting with a plane parallel interface between air and a material with complex index of refraction $\tilde{N}_2$.

In a dielectric material such as glass, n is an inverse measure of the phase velocity of light in the material, related to the speed of light in free space, that is,

$$n = \frac{c}{v} \tag{2.5}$$

In silicon nitride, where $n \approx 2$, the phase velocity of light is half that of light in free space.

The extinction coefficient k is a measure of how rapidly the intensity decreases as the light passes through the material. In order to gain a better understanding of the extinction coefficient, let us consider first, the *absorption coefficient*, which is denoted as α and is defined as follows. In an absorbing medium, the decrease in intensity I per unit length z is proportional to the value f I. In equation form, this is

$$\frac{dI(z)}{dz} = -\alpha I(z) \tag{2.6}$$

The solution to this equation is

$$I(z) = I_0 e^{-\alpha z} \tag{2.7}$$

where I_0 is the intensity of the light just inside the material of interest. (α is dependent on loss of intensity due to absorption only. Loss of light due to the reflection at the interfaces does not contribute to the magnitude of α.)

This is the familiar negative exponential function which approaches zero but never gets there. The extinction coefficient k is related[8] to the absorption coefficient by

$$k = \frac{\lambda}{4\pi}\alpha \tag{2.8}$$

TABLE 2.1 Penetration Depths (Defined in Text) for Several Materials

Material	Wavelength (λ)	Extinction Coefficient (k)	Penetration Depth (D_p)
Single crystal Si[9]	6328 Å	0.016	~ 3.1 μm
Single crystal Si[10]	3009 Å	4.09	58 Å
Tungsten[11]	6328 Å	2.63	191 Å
Aluminum[11]	6328 Å	6.92	73 Å

We characterize the curve defined by Eq. 2.7 with a quantity which we will call the *penetration depth*. When the quantity αz is equal to 1.0, from Eq. 2.7, the intensity will have decreased by a factor of e^{-1} (about 37%) of its original value. We define[8] the penetration depth as the depth where this occurs, and denote it as D_p. From Eq. 2.8, this is given by

$$D_p = \frac{\lambda}{4\pi k} \tag{2.9}$$

(Note that in Eqs. 2.8 and 2.9, λ is the wavelength of light in free space rather than in the medium itself.)

We shall find that both the index of refraction and the extinction coefficient are functions of wavelength. The term *optical constants* is somewhat inappropriate. In addition, these quantities are also functions of temperature. The term *optical functions* is sometimes used. In keeping with common usage, however, we shall use the older term and, when appropriate, use the term *optical constant spectra* to denote the index of refraction and the extinction coefficient plotted as a function of either wavelength or photon energy.

Some examples of penetration depths are given in Table 2.1. In the case of single-crystal silicon, we show the value of k at two different wavelengths. Note that at a thickness of D_p, the intensity has dropped to 37% of its initial value, at $2 \times D_p$, it has dropped to 15%, at $3 \times D_p$, to 5%, and at $4 \times D_p$, to 2%. Hence, optical measurements only *see* about four penetration depths of a given material.

2.2.2. Laws of Reflection and Refraction

As suggested by Figure 2.2, some of the light is reflected at the interface and some is transmitted into the material. It was known by the ancients (Euclid, 300 BC) that the angle of reflection is equal to the angle of incidence, that is,

$$\phi_i = \phi_r \tag{2.10}$$

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In Figure 2.2, both angles are listed as ϕ_1. The law of refraction is somewhat more involved and is called *Snell's law* after Willebrord Snell, who discovered the principal in 1621. Snell's law, in its most gen ral form, is

$$\tilde{N}_1 \sin \phi_1 = \tilde{N}_2 \sin \phi_2 \tag{2.11}$$

This is derived in Appendix C.

When dealing with a dielectric material, that is, $k = 0$, the law simplifies to the more familiar

$$n_1 \sin \phi_1 = n_2 \sin \phi_2 \tag{2.12}$$

All of the terms in Eq. 2.12 are real numbers. For Eq. 2.11, generally $k = 0$ for the ambient, hence $\tilde{N}_1$ is real, and the sine function for medium 1 is a real number (as we would expect). If $\tilde{N}_2$ is a complex number (k_2 is nonzero) then the sine function in medium 2 is a complex function rather than the familiar function (opposite side over the hypotenuse).[12] There is a corresponding complex cosine function such that

$$\sin^2 \phi_2 + \cos^2 \phi_2 = 1 \tag{2.13}$$

We shall find that we use the complex cosine function in Fresnel's equations and we use Eq. 2.13 along with Snell's law to determine its value.

2.3 POLARIZED LIGHT

2.3.1 Sources

When a given photon is emitted from an incandescent source, its electric field is oriented in a given direction. The electric field of the next photon will be oriented in a different direction, and in general photons are emitted with electric fields oriented in all different directions. This is called *unpolarized* light. If we arrange for all the photons in our light beam to be oriented in a given direction, the light is referred to as *polarized* light. One familiar way to do this is to pass the light through an optical element which only allows light having one particular orientation to pass through. Another method is to have a light source which emits polarized light. Whereas incandescent light sources are unpolarized, most lasers emit light which is more or less polarized.

2.3.2 Linearly Polarized Light

In Figure 2.3, we depict the electric field strength for two light beams with the same frequency and the same amplitude traveling along the same path. We have offset them in the drawing for clarity. One is polarized in the vertical

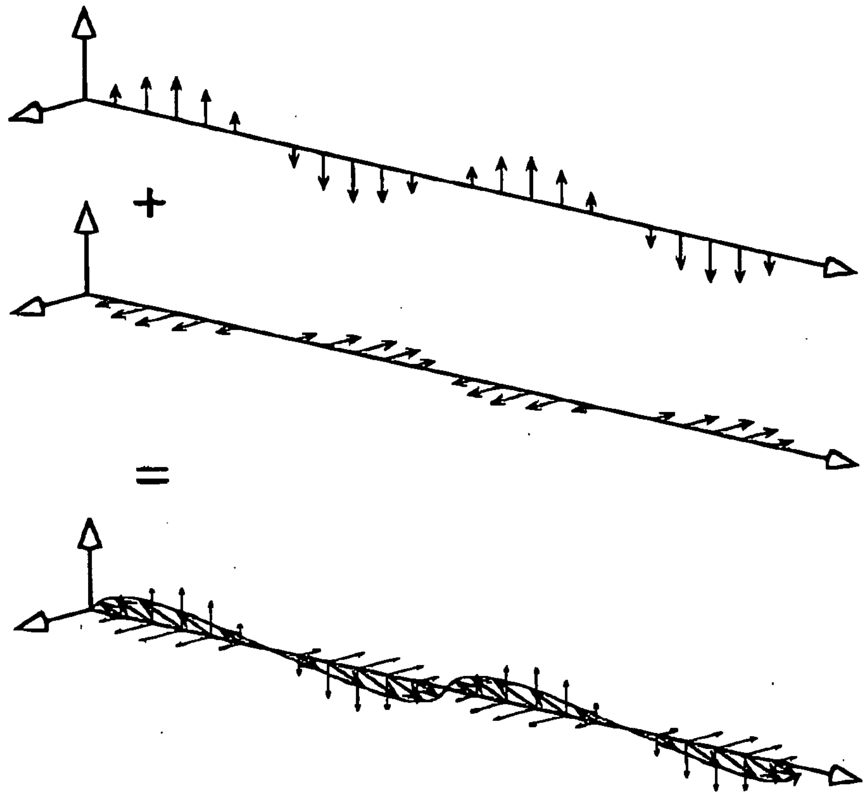

Figure 2.3 Combining two linearly polarized light beams which are in phase and have the same frequency produces linearly polarized light.

direction and one is polarized in the horizontal direction. In this case, note specifically that the maximum, minimum, and zero points of the vertical wave coincide with those of the horizontal wave, that is, the waves are *in phase*. When the vector sums of the components of the two waves are added at each point in space, the resultant wave is a linear wave which is polarized at 45° to the vertical. If all other conditions were the same, but the amplitudes were not equal, the result would have been a linear polarized wave at an angle different from 45°. Specifically, *when two linearly polarized waves with the same frequency are combined in phase, the resultant wave is linearly polarized.*

2.3.3 Elliptically Polarized Light

In Figure 2.4, we again depict two light beams with the same frequency and amplitude traveling along the same path. Again, one is polarized vertically and

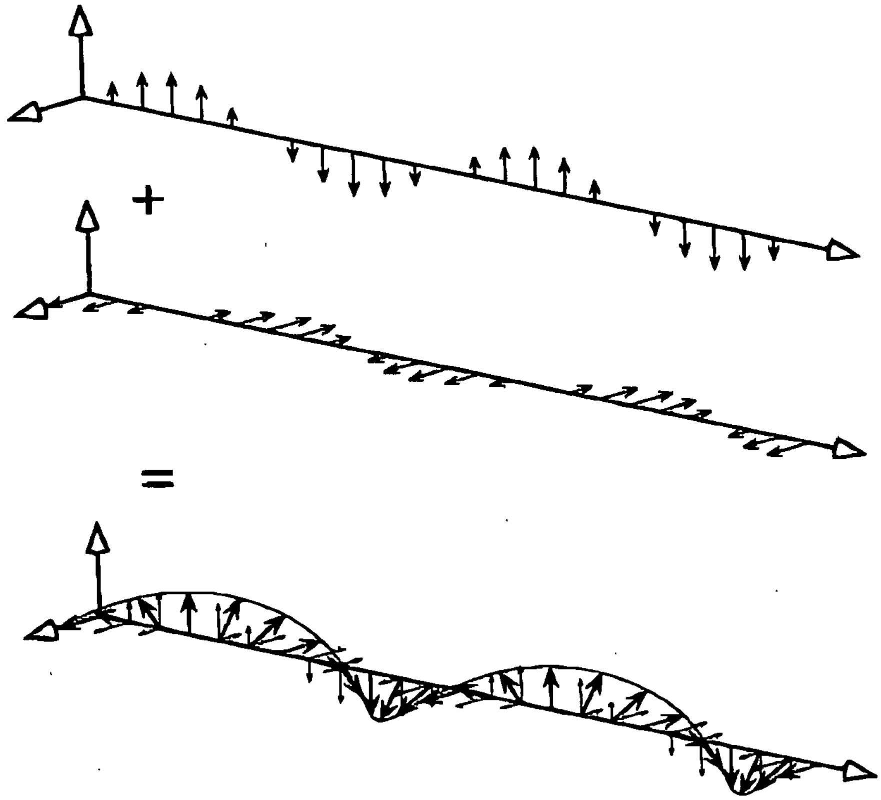

Figure 2.4 Combining two linearly polarized light beams which are a quarter wave out of phase and which have the same frequency and amplitude will produce circularly polarized light.

the other is polarized horizontally. In this case, however, the maximum, zero, and minimum of the electric field strength of the horizontal wave have been displaced from those of the vertical wave (in this particular example, the two waves are *out of phase* by 90°.) When the two waves are combined, the tips of the arrows of the resultant wave do not move back and forth in a plane, as was the case in the previous illustration. Instead, they move in a manner which, if viewed end-on, would describe a circle. This is called circularly polarized light. Had the phase shift been anything other than 90°, or had the amplitudes not been equal, the tips of the arrows would have appeared to be moving on an ellipse, if viewed end-on, and this is referred to as elliptically polarized light. Specifically, *when two linearly polarized waves with the same frequency are combined out of phase, the resultant wave is elliptically polarized.* Linearly polarized light and circularly polarized light are specific cases of the more general elliptically polarized light.

2.3.4 Application of Elliptically Polarized Light

The light used in most reflectometry instruments is not intentionally polarized. Elliptically polarized light is used in ellipsometry, and in fact is the reason for the name ellipsometry. Elliptically polarized light is generated when linearly polarized light reflects from a surface under certain conditions. The amount of ellipticity which is induced depends on the surface (optical constants, presence of films, etc.). A second method for changing the ellipticity of polarized light is to pass the light beam through certain specific optical elements. By directing our light beam at materials of interest, we use it as a probe. We use our optical elements to determine how much ellipticity was induced from the reflection and then calculate from this the properties (optical constants, thicknesses of films, etc.) of our material of interest.

2.4 THE REFLECTION OF LIGHT

2.4.1 Orientation

Both reflectometry and ellipsometry involve the light making a reflection from the surface of interest. In order to write the equations which describe the effect of the reflection on the incident light, it is necessary to define a reference plane. Figure 2.5 shows schematically a light beam reflecting from the surface. The incident beam and the direction normal to the surface define a plane which is perpendicular to the surface and this is called the *plane of incidence*. Note that the outgoing beam is also in the plane of incidence. As indicated in Figure 2.2, the angle of incidence is the angle between the light beam and the normal to the surface. The effect of the reflection depends on the polarization state of the incoming light and the angle of incidence. In Figure 2.5 we show the amplitude of the electric wave which is waving in the plane of incidence as E_p and the amplitude of the electric wave which is waving perpendicular to the plane of

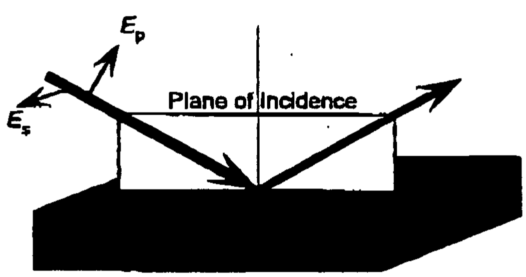

Figure 2.5 The plane of incidence is defined as the plane which contains both the incoming beam and the normal to the surface. The amplitude of the electric field wave in the plane of incidence and perpendicular to the plane of incidence are called E_p and E_s, respectively.

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incidence as E_s. These waves are referred to as p-waves and s-waves, respectively. The subscripts "s" and "p" stand for the German words "senkrecht" and "parallel."

2.4.2 The Reflection Equations of Fresnel

The reflectance, denoted herein as "$\Re$", is the ratio of the *intensity* of the outgoing light compared to that of the incoming light. This is the quantity which is measured in all reflectance instruments. Recall that the intensity is proportional to the square of the amplitude of the wave.

In addition to the reflectance, we are also interested in the ratio of the *amplitude* of the outgoing wave compared to that of the incoming wave. We first focus on a single interface and will develop the more general case later. When only one interface is considered, this ratio is called the *Fresnel reflection coefficient*, and it will be different for s-waves and p-waves. As suggested by Figure 2.2, let us suppose that the interface separates medium 1 and medium 2, with respective indices of refraction $\tilde{N}_1$ and $\tilde{N}_2$ and angles of incidence and refraction ϕ_1 and ϕ_2 (related by Snell's law). When the beam is incident from medium 1 onto medium 2, the Fresnel reflection coefficients are given by

$$r_{12}^{p} = \frac{\tilde{N}_2 \cos\phi_1 - \tilde{N}_1 \cos\phi_2}{\tilde{N}_2 \cos\phi_1 + \tilde{N}_1 \cos\phi_2} \qquad r_{12}^{s} = \frac{\tilde{N}_1 \cos\phi_1 - \tilde{N}_2 \cos\phi_2}{\tilde{N}_1 \cos\phi_1 + \tilde{N}_2 \cos\phi_2} \tag{2.14}$$

where the superscripts refer to either p-waves or s-waves and the subscripts refer to the media which the interface separates. Corresponding equations exist for transmission. The reflection and transmission coefficient equations are derived in Appendix C.

2.4.3 The Brewster Angle

For light incident from air onto dielectrics, that is, when $k = 0$, all of the terms in the Fresnel equations above are real numbers. Figure 2.6A shows a plot of both of the Fresnel coefficients as a function of angle of incidence for a material such as TiO_2 which has an index of refraction $n = 2.2$ at a wavelength of 6328 Å. At normal incidence, r^p and r^s have equal magnitudes but opposite signs. For a single interface, the reflectance is simply the square of the Fresnel reflection coefficient. Figure 2.6B shows the reflectance, $\Re$, also plotted versus angle of incidence. At normal incidence, all of the cosine terms are equal to +1 and we have

$$r_{12}^{p} = \frac{n_2 - 1}{n_2 + 1} \qquad r_{12}^{s} = \frac{1 - n_2}{1 + n_2} \qquad \Re^{p} = \Re^{s} = \left(\frac{n_2 - 1}{n_2 + 1}\right)^2 \tag{2.15}$$

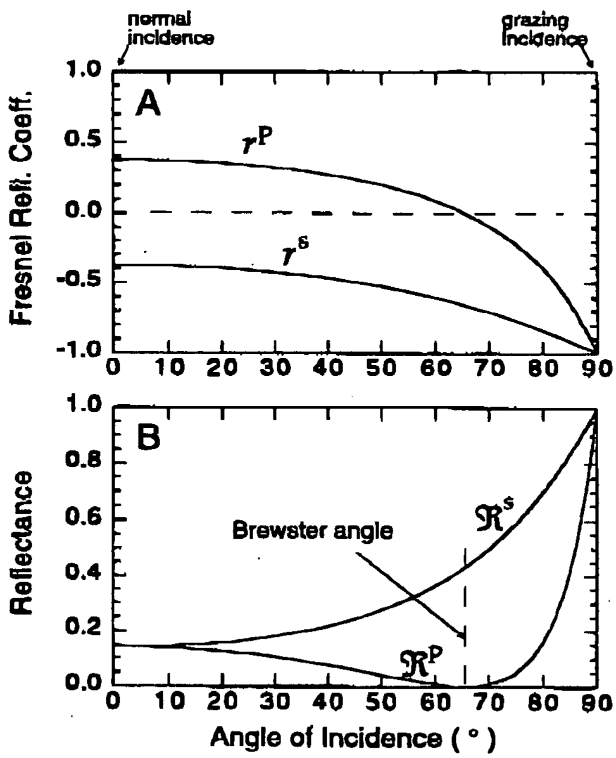

Figure 2.6 (A) The Fresnel reflection coefficients, and (B) the reflectance, plotted versus the angle of incidence for light incident from air onto a dielectric such as TiO_2 with $n = 2.2$ and $k = 0$, at a wavelength of 6328 Å. At the Brewster angle, all of the reflected light is polarized with the electric vector perpendicular to the plane of incidence.

The reflectance of the two waves must be equal at normal incidence since the plane of incidence is no longer uniquely defined.

For other than normal incidence, we see that r^s is always negative and nonzero, whereas r^p is positive for angles near-normal, passes through zero, and is negative for near-grazing angles of incidence. This can be rationalized algebraically[13] from the relationship $n_2 > n_1$ and $\cos \phi_1 > 0$.

At the angle of incidence where r^p is zero, the reflectance $\Re^p$ is also zero; hence all of the reflected light is polarized perpendicular to the plane of incidence. This is shown in Figure 2.6 as the *Brewster angle*. This phenomena was discovered by David Brewster[14] in the early 1800s. This angle is also known as the *polarizing angle* and sometimes the *principal angle*.

Two significant ramifications of the Brewster angle are that at that angle, designated as ϕ_B,

$$\tan \phi_B = \frac{n_2}{n_1} \tag{2.16}$$

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$$\cos \phi_2 = \sin \phi_B \tag{2.17}$$

which is to say that the angle between the reflected beam and the transmitted beam is a right angle. One additional feature of the Brewster angle for dielectrics is that this is the incidence angle where the phase shift of the p-wave on reflection shifts abruptly from zero to 180°. No such shift occurs for the s-wave.

The Brewster angle is a function of the index of refraction and, as indicated earlier, the index of refraction is a function of wavelength; hence the Brewster angle is a function of wavelength. The term *Brewster wavelength* is sometimes used with a single angle of incidence. This is simply the wavelength where the value of the index of refraction matches the Brewster condition for that angle of incidence.

The concept of the Brewster angle or polarizing angle is used routinely by photographers in photographing objects which are under water. The light coming from the underwater object (fish or alligators) is often significantly less that the light reflected from the top surface of the water, and the reflected light will obscure the underwater object. If the angle of incidence of the reflected light is roughly equal to the Brewster angle, a polarizer adjusted to the correct azimuth will remove the reflected light, allowing the camera to capture the light from the underwater object.

At the Brewster angle, although the reflected light is polarized in one direction only, the transmitted light still has components of both polarizations. Multiple interfaces can be used to remove successively more and more of the perpendicular polarized light until the transmitted light is virtually pure polarized light in the plane of incidence. Historically,[15] this is one method of obtaining polarized light.

When the reflecting surface is not a dielectric, that is, k is nonzero, the situation becomes more complicated. The Fresnel reflection coefficients r^p and r^s are now complex numbers and the concepts of greater than zero and less than zero have no meaning. Normally, there is no situation where both the real and imaginary parts of the complex number are zero; hence there is no analogous version for Figure 2.6A for metals or semiconductors. The reflectance values, $\Re^p$, and $\Re^s$, are real numbers, however, defined as the square of the magnitudes of r^p and r^s, and can be plotted, as shown in Figure 2.7, for tantalum. Although $\Re^p$ does not go to zero, it does go through a minimum at an angle which is called the principal angle.

As the angle of incidence increases, the phase difference between the p-wave and the s-wave shifts gradually, rather than abruptly as for a dielectric (at the Brewster angle). For metals, as for all other materials, the phase difference passes through 90° at the principal angle. This will be discussed in detail in Chapter 6 (see Figure 6.3).

It should be noted that high reflectance is obtained when the index of the substrate is significantly different from that of the ambient. This can occur

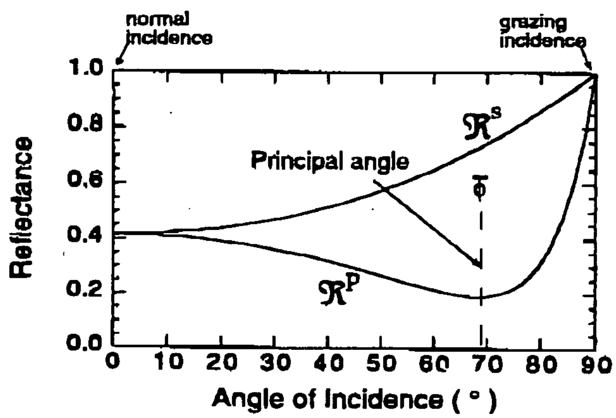

Figure 2.7 The reflectance, plotted versus the angle of incidence for a metal such as Ta with $n = 1.72$ and $k = 2.09$ at a wavelength of 6328 Å.

when n_2 is significantly different from 1.0 or when k_2 is large (significantly different from zero).

2.4.4 Reflections with Films

When more than one interface is present, that is, with a film, the light which is transmitted across the first interface cannot be ignored, as was the case in the previous section. As suggested by Figure 2.8, the resultant reflected wave returning to medium 1 will consist of light which is initially reflected from the first interface as well as light which is transmitted by the first interface, reflected from the second interface, and then transmitted by the first interface going in the reverse direction, and so on. Each successive transmission back

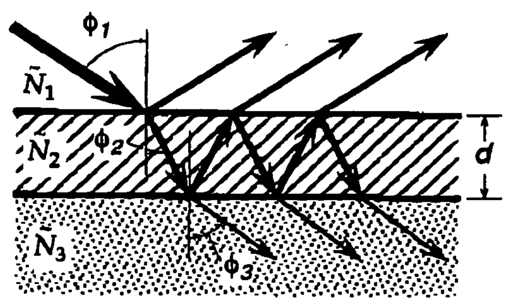

Figure 2.8 Reflections and transmissions for two interfaces. The resultant reflected beam is made up of the initially reflected beam and the infinite series of beams which are transmitted from medium 2 back into medium 1.

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2.5 ELLIPS

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From a macroscopic point of view, the quantities of interest are the amplitude of the incoming wave and the amplitude of the resultant outgoing wave. For the reflectometry technique, we are interested in the intensity, or the square of the amplitude. For the ellipsometry technique, we are interested in the phase and amplitude relationships between the p-wave and the s-wave.

The ratio of the amplitude of the outgoing resultant wave to the amplitude of the incoming wave is defined as the *total reflection coefficient*, and is analogous to the Fresnel reflection coefficients for a single interface. For a single film (two interfaces) this is

$$R^{p} = \frac{r_{12}^{p} + r_{23}^{p}\exp(-j2\beta)}{1 + r_{12}^{p}r_{23}^{p}\exp(-j2\beta)} \qquad R^{s} = \frac{r_{12}^{s} + r_{23}^{s}\exp(-j2\beta)}{1 + r_{12}^{s}r_{23}^{s}\exp(-j2\beta)} \tag{2.18}$$

where

$$\beta = 2\pi\left(\frac{d}{\lambda}\right)\tilde{N}_2 \cos\phi_2 \tag{2.19}$$

These equations are derived in Appendix C.

When $k \neq 0$ the Fresnel coefficients, $\tilde{N}_2$, and $\cos\phi_2$ (and hence β) are complex numbers. When $k = 0$, these numbers are real. In general, except for very special circumstances, R^p and R^s are complex numbers. β is the phase change in the wave, as it moves from the top of the film to the bottom of the film. Hence, 2β is the phase difference between the part of the wave reflecting from the top surface and the part of the wave which has traversed the film twice (in and out).

For multiple films, the expressions on the right-hand side of Eq. 2.18 can be used in an iterative way[16,17] to determine the total reflection coefficient for the entire stack. For the rapid calculation needed in regression analysis,[18] some form of a matrix method is often used.

2.6 ELLIPSOMETRY AND REFLECTOMETRY DEFINITIONS

2.5.1 Reflectance

The reflectance is defined as the ratio of the intensity of the outgoing wave to the intensity of the incoming wave. The total reflection coefficients R^p and R^s are defined above as the ratio of the amplitude of the outgoing wave to the amplitude of the incoming wave. Hence, the reflectance is the square of the magnitude of the total reflection coefficient, that is,

$$\Re^{p} = |R^{p}|^2 \qquad \text{and} \qquad \Re^{s} = |R^{s}|^2 \tag{2.20}$$

For a single interface (no film), the total reflection coefficients reduce to the Fresnel reflection coefficients.

Most reflectance measurements are made at normal or near-normal incidence. Under these conditions, all of the cosine terms are equal to unity, and as suggested in Eq. 2.15, there is no distinction between the p-waves and the s-waves.

2.5.2 Delta and Psi

Figure 2.5 shows the p-waves and s-waves and, in general, they are not necessarily in phase. When each makes a reflection, there is the possibility of a phase shift and the shift is not necessarily the same for the different waves. Let us denote the phase difference between the p-wave and the s-wave before the reflection as δ_1 and the phase difference after the reflection as δ_2. We define the parameter Δ, called *delta* (and often abbreviated as *Del*), as

$$\Delta = \delta_1 - \delta_2 \tag{2.21}$$

Delta, then, is the phase shift which is induced by the reflection, and its value can be from $-180°$ to $+180°$ (or alternatively, from zero to 360°).

In addition to a phase shift, the reflection will also induce an amplitude reduction for both the p-wave and the s-wave, and again, it will not necessarily be the same for the two types of wave. The total reflection coefficient for the p-wave and for the s-wave is defined as the ratio of the outgoing wave amplitude to the incoming amplitude and, in general, this is a complex number. $|R^p|$ and $|R^s|$ are the magnitudes of these amplitude diminutions. We define the quantity Ψ in such a manner that

$$\tan \Psi = \frac{|R^p|}{|R^s|} \tag{2.22}$$

Ψ is the angle whose tangent is the ratio of the magnitudes of the total reflection coefficients, and its value can range from zero to 90°.

2.5.3 The Fundamental Equation of Ellipsometry

Whereas $\tan \Psi$ is defined as the ratio of the magnitudes of the total reflection coefficients, and is hence a real number, we define a complex number ρ (rho) to be the complex ratio of the total reflection coefficients, that is,

$$\rho = \frac{R^p}{R^s} \tag{2.23}$$

The fundamental equation of ellipsometry[19] then is

$$\rho = \tan \Psi e^{j\Delta} \quad \text{or} \quad \tan \Psi e^{j\Delta} = \frac{R^p}{R^s} \tag{2.24}$$

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The magnitude of ρ is contained in the $\tan\Psi$ part and the phase of ρ is contained in the exponential function. The quantities Ψ and Δ (sometimes only $\cos\Delta$) are measured by ellipsometers. These are properties of our probing light beam. The information about our sample is contained in the total reflection coefficients, and hence in ρ. It should be noted that assuming that our instrument is operating correctly, the quantities Δ and Ψ which are measured are always correct. Whether the quantities such as thickness and the optical constants which we deduce are correct or not depends on whether or not we have assumed the correct model. As an example of this, incorrect values of n and k can be deduced if we assume that our material is a substrate when in fact we have a thin layer of one material on top of a substrate of another material.

This simply makes the point that the quantities which ellipsometers measure are Δ and Ψ. Quantities such as thickness are calculated quantities based on an assumed model.

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